

WS1: one more new Galactic bona fide luminous blue variable^{*}

A. Y. Kniazev,^{1,2,3†} V. V. Gvaramadze,^{3,4,5} L. N. Berdnikov^{6,3,5}

¹*South African Astronomical Observatory, PO Box 9, 7935 Observatory, Cape Town, South Africa*

²*Southern African Large Telescope Foundation, PO Box 9, 7935 Observatory, Cape Town, South Africa*

³*Sternberg Astronomical Institute, Lomonosov Moscow State University, Universitetskij Pr. 13, Moscow 119992, Russia*

⁴*Space Research Institute, Russian Academy of Sciences, Profsoyuznaya 84/32, Moscow 117997, Russia*

⁵*Isaac Newton Institute of Chile, Moscow Branch, Universitetskij Pr. 13, Moscow 119992, Russia*

⁶*Astronomy and Astrophysics Research division, Entoto Observatory and Research Center, P.O.Box 8412, Addis Ababa, Ethiopia*

Accepted 2015 February 3. Received 2015 February 3; in original form 2014 November 24

ABSTRACT

In this Letter, we report the results of spectroscopic and photometric monitoring of the candidate luminous blue variable (LBV) WS1, which was discovered in 2011 through the detection of a mid-infrared circular shell and follow-up optical spectroscopy of its central star. Our monitoring showed that WS1 brightened in the *B*, *V* and *I* bands by more than 1 mag during the last three years, while its spectrum revealed dramatic changes during the same time period, indicating that the star became much cooler. The light curve of WS1 demonstrates that the brightness of this star has reached maximum in 2013 December and then starts to decline. These findings unambiguously proved the LBV nature of WS1 and added one more member to the class of Galactic bona fide LBVs, bringing their number to sixteen (an updated census of these objects is provided).

Key words: line: identification – stars: emission-line, Be – stars: evolution – stars: individual: [GKM2012] WS1 – stars: massive.

1 INTRODUCTION

Luminous blue variables (LBVs) are hot luminous supergiant stars showing strong photometric and spectral variability on time-scales from years to decades (Humphreys & Davidson 1994; van Genderen 2001). The origin of this variability is still poorly understood, partly because of the small number (about a dozen) of confirmed members of this class of massive evolved stars. It is believed that during the LBV phase, the massive stars lose a significant fraction of their mass, which play an important role in their subsequent evolution (Langer et al. 1994) and is manifested in the presence of circumstellar nebulae around the majority of LBVs (Nota et al. 1995; Clark, Larionov & Arkharov 2005). Detection of nebulae reminiscent of those associated with LBVs and related stars provides a powerful tool for revealing evolved massive stars (Waters et al. 1996; Egan et al. 2002; Clark et al. 2003; Gvaramadze et al. 2009, Gvaramadze, Kniazev

& Fabrika 2010c; Gvaramadze et al. 2010a; Wachter et al. 2010; Burgemeister et al. 2013). There are also indications that LBVs might be immediate progenitors of supernovae (Kotak & Vink 2006; Smith et al. 2007; Groh, Meynet & Ekström 2013). This makes them particularly interesting objects to study because some of the already known LBVs could soon end their lives in spectacular explosions. Disclosing of new members of this class of evolved massive stars is therefore of high importance.

Recent searches for LBVs using follow-up spectroscopy of candidate evolved massive stars, revealed through detection of their mid-infrared circumstellar nebulae with the *Spitzer Space Telescope* and *Wide-field Infrared Survey Explorer* (*WISE*), resulted in nearly doubling the number of stars with spectra typical of LBVs (Gvaramadze et al. 2010a,b, 2012, 2014; Wachter et al. 2010, 2011; Stringfellow et al. 2012a,b; Flagey et al. 2014). However, only few of these stars show variability inherent to bona fide LBVs (e.g. Gvaramadze et al. 2014), while others are in a quiescent state since their discovery and are considered as candidate LBVs (cLBVs). It is worthy therefore to monitor the known cLBVs to search for their expected spectral and photometric variability.

^{*} Based on observations obtained with the Southern African Large Telescope (SALT), programmes 2010-1-RSA_OTH-001, 2013-1-RSA_OTH-014 and 2013-2-RSA_OTH-003.

[†] E-mail: akniazev@sao.ac.za

In this Letter, we report the results of spectroscopic and photometric monitoring of WS1 – one of the two cLBVs discovered in Gvaramadze et al. (2012; Paper I hereafter) through the detection of circular shells with *WISE* and follow-up spectroscopy of their central stars with the Southern African Large Telescope (SALT). Using archival and contemporary photometry, we found in Paper I that WS1¹ brightened in the *R* and *I* bands by 0.68 ± 0.10 mag and 0.61 ± 0.04 mag, respectively, during 13–18 yr. This prompted us to continue observations of WS1 (Section 2), which unambiguously proved the LBV nature of WS1 (Section 3) and added one more member to the class of Galactic bona fide LBVs, bringing their number to sixteen (see Section 4 for the current census of these stars).

2 OBSERVATIONS OF WS1

2.1 SALT spectroscopy

The first spectrum of WS1 was obtained with the SALT (Buckley, Swart & Meiring 2006; O’Donoghue et al. 2006) on 2011 June 12 with the Robert Stobie Spectrograph (Burgh et al. 2003; Kobulnicky et al. 2003) in the long-slit mode. This spectrum was presented for the first time and discussed in detail in Paper I. It shows strong H and He I emission lines, numerous prominent metal lines of N II, Fe III and Si II in emission, and the weak He II $\lambda 4686$ emission (see figs 3–5 in Paper I and Fig. 1), which are typical of hot LBVs during the visual minimum (e.g. Stahl et al. 2001). Based on this spectrum and photometric variability (see Section 1), and the presence of a mid-infrared shell around WS1 (see fig. 1 in Paper I), we classified this star as a cLBV.

In the course of spectral monitoring of WS1 in 2013–2014, we obtained seven more spectra with the SALT. The PG900 grating was used for these observations. In all cases, the spectral range of 4200 – 7300 Å was covered with a final reciprocal dispersion of $0.97 \text{ Å pixel}^{-1}$. The spectral resolution full width at half-maximum (FWHM) was of $5.05 \pm 0.15 \text{ Å}$. In most cases, one short exposure was obtained additionally to get non-saturated H α line. A Xe lamp arc spectrum was taken immediately after all science frames. Spectrophotometric standard stars were observed during twilight time for relative flux calibration. Absolute flux calibration is not feasible with SALT because the unfilled entrance pupil of the telescope moves during the observations. The log of all our spectroscopic observations of WS1 is listed in Table 1.

Primary reduction of the data was done in the standard way with the SALT science pipeline (Crawford et al. 2010). Following long-slit data reduction was carried out in the way described in Kniazev et al. (2008).

2.2 Photometry

To search for photometric variability of WS1, we occasionally obtained its CCD photometry with the 76-cm telescope of the South African Astronomical Observatory during our observing runs in 2011–2014. We used an SBIG ST-10XME CCD camera equipped with *BVI_c* filters of the

Table 1. Journal of the observations.

Date	Exposure (min)	Slit/Seeing (arcsec)	JD (d)
2011 June 12 ^a	3×10	1.00/2.1	2455725
2013 April 22	1×1, 1×10	1.25/1.0	2456405
2013 May 23	1×1, 1×10	1.25/2.0	2456436
2013 June 18	1×0.5, 1×5	1.25/2.5	2456462
2013 July 22	1×1, 1×10	1.25/2.5	2456496
2014 January 13	2×1, 1×13	1.25/3.5	2456671
2014 March 13	1×1, 1×10	1.25/1.5	2456730
2014 April 18	1×10	1.25/1.6	2456766

^aPresented for the first time in Paper I.

Kron-Cousins system (for details see Berdnikov et al. 2012). The results are presented in Table 2. To this table we also added archival photometry from Paper I, which is based on the data from the USNO B-1 catalogue (Monet et al. 2003), and photometry derived from two unsaturated *V* and *I* band acquisition images obtained with the SALT and calibrated using the secondary photometric standards established from the 76-cm telescope data.

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Fig. 1 presents a montage of all eight (normalized) spectra of WS1 with the date of the observations (listed in Table 1) increasing from top to bottom. Comparison of the 2011’s spectrum with those obtained in 2013–2014 revealed dramatic changes in its appearance. One can see that already in the second spectrum (2013 April 22) the He I emission lines are almost disappeared. Similarly, Fe III lines are disappeared as well, while numerous Fe II emissions became prominent. Besides, most of the N II and Si II lines changed from emission in 2011 into almost pure absorption in the later spectra. All these changes are typical of bona fide LBVs (e.g. Stahl et al. 2001, Groh et al. 2009) and indicate that the effective temperature, T_{eff} , of WS1 has decreased drastically during the last one and half years.

In Paper I, we noted that the spectrum of WS1 is very similar to that of the bona fide LBV AG Car during the epoch of a minimum in 1985–90, when it was a WN11 star (Stahl et al. 2001) with $T_{\text{eff}} \approx 22\,000 \text{ K}$ (Groh et al. 2009), and argued that WS1 could be classified as WN11 as well. Using the Stellar Spectral Flux Library by Pickles (1998), we also found the colour excess towards WS1 of $E(B - V) = 2.40$ mag by matching the dereddened spectral slope of this star with those of stars of similar T_{eff} . Applying the same $E(B - V)$ to deredden the 2013–2014 spectra of WS1, we found that its T_{eff} decreased to $\approx 12\,000 \text{ K}$ by 2013 April 22 and remained around this value ever since.

With the above temperature estimates, one can attempt to check whether the spectrophotometric variability of WS1 is accompanied by a change in the bolometric luminosity (cf. Clark et al. 2009; Groh et al. 2009; Maryeva & Abolmasov 2012). Using the *V* magnitudes from Table 2 and adopting the visual bolometric corrections of ≈ -2.4 and -0.8 mag, respectively, for the hot and cool states of WS1 (cf. Groh et al. 2009; Crowther, Lennon & Walborn 2006), one finds that the bolometric luminosity has decreased by a factor

¹ Named in the SIMBAD data base as [GKM2012] WS1.

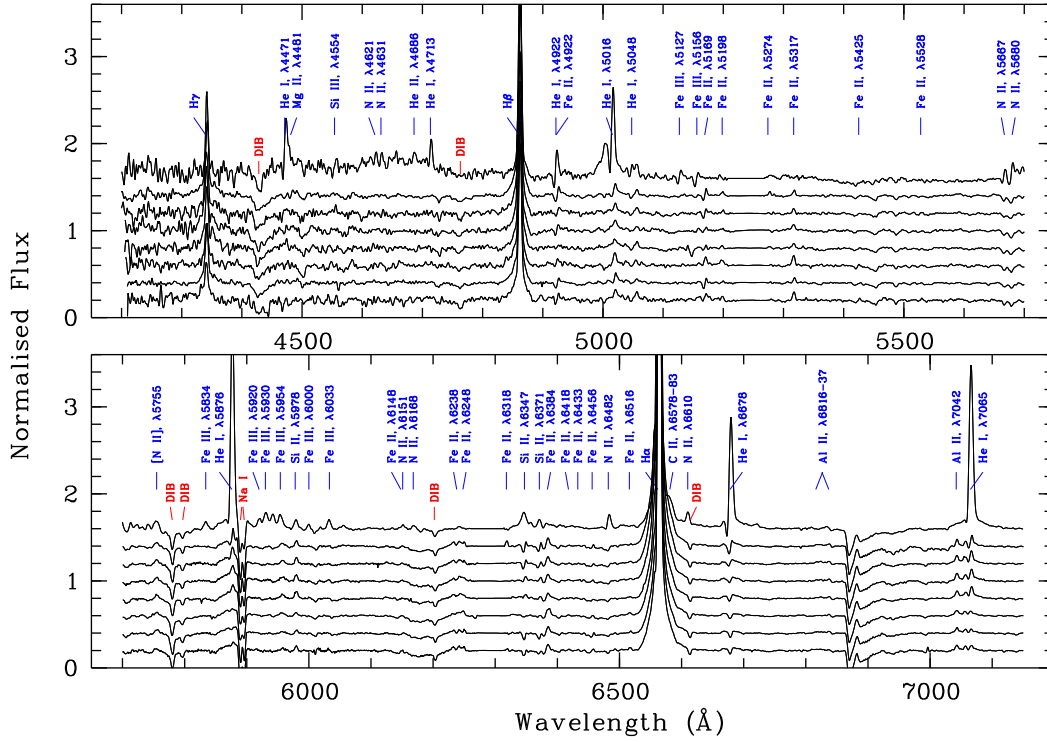


Figure 1. Evolution of the (normalized) spectrum of WS1 since its discovery in 2011 (from top to bottom; see Table 1 for the dates of the observations). Principal lines and most prominent diffuse interstellar bands (DIBs) are indicated. For clarity, the spectra are offset by 0.2 continuum flux unit.

Table 2. Archival and contemporary photometry of WS1. The measurements were obtained with the 76-cm telescope, unless otherwise is noted.

Date	<i>B</i>	<i>V</i>	<i>I</i>	JD
1976 March 8 ^a	17.50±0.10	—	—	2442846
1979 June 7 ^a	—	—	12.60±0.10	2444032
2011 June 12 ^b	—	15.25±0.04	—	2455725
2011 September 23 ^b	17.36±0.03	15.31±0.03	12.18±0.03	2455828
2011 December 10	17.05±0.06	14.93±0.03	11.94±0.01	2455905
2012 May 6	16.61±0.03	14.50±0.01	11.36±0.01	2456053
2013 January 13	16.23±0.03	14.06±0.01	10.84±0.01	2456305
2013 May 23 ^c	—	13.98±0.03	—	2456436
2013 December 31	16.05±0.03	13.85±0.01	10.74±0.01	2456657
2014 January 13	16.04±0.03	13.91±0.01	10.74±0.01	2456670
2014 January 19	16.06±0.03	13.90±0.01	10.78±0.01	2456676
2014 January 26	16.05±0.03	13.90±0.01	10.76±0.01	2456683
2014 March 31	16.07±0.03	13.86±0.02	10.77±0.02	2456748
2014 April 9	16.14±0.03	13.92±0.02	10.82±0.02	2456757
2014 April 16	16.23±0.03	13.96±0.02	10.81±0.02	2456764
2014 April 18 ^c	—	—	10.78±0.04	2456766
2014 May 12	16.20±0.03	13.99±0.02	10.86±0.02	2456790

^aUSNO B-1; ^bPaper I; ^cSALT.

of 1.2. Whether this modest decrease is real or simply a result of inaccuracy of our estimate could be proved with a detailed spectral analysis of WS1, which is, however, beyond the scope of this Letter and will be presented elsewhere.

The only forbidden line visible in the spectra, [N II] $\lambda 5755$, is also weakened considerably. Its FWHM could be used to derive the stellar wind velocity, v_∞ (cf. Leitherer et al. 1985). Fig. 2 (upper panel) shows evolution of v_∞ from

spectrum to spectrum. As expected, the wind velocity slows down significantly with the decrease of T_{eff} , reaching its minimum value of $\approx 40 \pm 20 \text{ km s}^{-1}$ near the visual maximum of WS1, then it increased by almost six times during about a half year and then slows down again by a factor of 2 during the next three months along with the brightness decline of the star (cf. Fig 3). It is likely that these changes in v_∞ reflect changes in the escape velocity from the stellar surface,

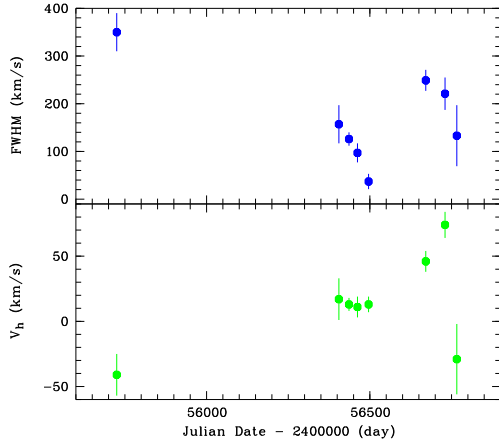


Figure 2. Changes of the FWHM and v_h of the [N II] $\lambda 5755$ line with time (1σ errors are indicated by vertical bars).

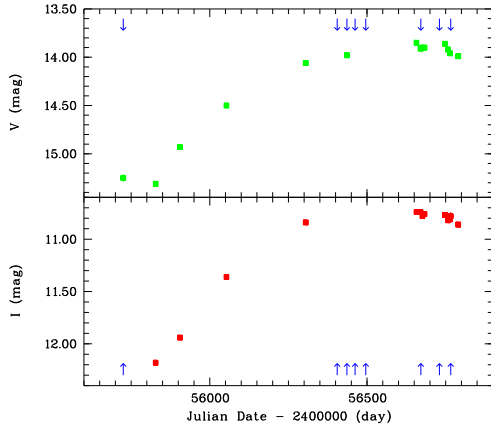


Figure 3. Light curves of WS1 in the V and I bands since its discovery in 2011. 1σ error bars are indicated, but in most cases they are within the size of the data points (boxes). The arrows mark the dates of the SALT spectra.

which is inversely proportional to the stellar radius, R_* , and therefore should be minimum at the visual maximum of the star when R_* reaches its maximum value (e.g. Stahl et al. 2001; Leitherer et al. 1994; Groh et al. 2009). It is worth noting that similar changes in v_∞ were revealed in AG Car, which decreased from 250 to 50 km s^{-1} on a time-scale of about one year (Leitherer et al. 1994).

It is also believed that the heliocentric radial velocity, v_h , of the [N II] $\lambda 5755$ line could be used to estimate the systemic velocity of the star (Stahl et al. 2001). For WS1 this method, however, does not work because v_h of the [N II] line varies from spectrum to spectrum (see the lower panel of Fig. 2). This variability may be caused by changes in the wind velocity.

Fig. 3 plots V and I band light curves of WS1 since the discovery of this star in 2011 with arrows indicating times when the spectra were obtained with the SALT. For each data point (square) we give 1σ error bars, which in most cases are less than the size of the squares themselves and therefore they cannot be discerned. One can infer from Fig. 3

and Table 2 that WS1 brightened almost smoothly in the B , V and I bands until the end of 2013 with the net brightness increase of ≈ 1.3 mag in the B band and ≈ 1.5 mag in the other two ones. Since then the brightness of the star declines. Thanks to the good time cadence of observations in 2014, one can see that the brightness decrease is not smooth, but is accompanied by short-term small-amplitude variability. Correspondingly, one cannot exclude the possibility that the overall brightening of WS1 in 2011–2013 was accompanied by the similar (or higher amplitude) variability as well.

The brightness increase of WS1 would be even higher if one takes into account the archival photometry. From Table 2 it follows that WS1 has brightened in the B and I bands by ≈ 1.5 and 1.9 mag, respectively, in last ≈ 40 yr. We caution, however, that during this time interval WS1 may well experience several S Dor-like outbursts and that the archival photometry might correspond to one of the brightness minima on the light curve of this star.

To conclude, our photometric and spectroscopic observations indicate that currently WS1 experiences an S Dor-like outburst and that this star has already passed through the maximum of its visual brightness.

4 GALACTIC BONA FIDE LBVS

The census of Galactic confirmed and cLBVs presented in Clark et al. (2005) lists 12 and 23 stars, respectively. About 60 per cent of these stars are associated with compact circular or bipolar circumstellar nebulae. Table 3 updates the list of the bona fide LBVs. (A current census of the cLBVs will be presented elsewhere.) The stars are arranged according to their right ascension, which increases in the table from left to right and from top to bottom. The names of three bona fide LBVs listed in Clark et al. (2005) cannot be recognized by the SIMBAD data base. For these stars we give their recognizable names and, for convenience, in parentheses we give their names from Clark et al. (2005).

Table 3 contains four new confirmed LBVs (marked by bold face). MWC 930 was suggested as a cLBV quite long ago (Miroshnichenko et al. 2005) and its LBV status was confirmed this year (Miroshnichenko et al. 2014). Discovery of a circular shell around MWC 930 (Cerrigone et al. 2014) lends an additional support to the LBV status of this star. [MMC2010] LBV G0.120-0.048 was discovered by Mauerhan et al. (2010) in the spectroscopic follow-up of unidentified point sources of Paschen- α ($P\alpha$) line excess in the Galactic Centre. The LBV status of this star was supported by its LBV-like spectrum, the already known photometric variability (≈ 1 mag during several years) and the presence of a circular nebula of $P\alpha$ emission centred on the star. Two other new LBVs, Wray 16-137 (Gvaramadze et al. 2014) and WS1, were first identified as cLBVs through the detection of circular shells and follow-up spectroscopy of their central stars, and then confirmed as LBVs thanks to the detection of major changes in their brightness and spectral appearance.

It is worthy to note that all four new bona fide LBVs are surrounded by circular shells, which raises the percentage of these stars associated with circumstellar nebulae to ≈ 70 per cent.

Table 3. Census of the Galactic bona fide LBVs. The LBVs detected after a similar census by Clark et al. (2005) was published are marked by bold face. The objects with detected circumstellar nebulae are starred.

HR Car*	η Car*	AG Car*	Wray 15-751* (Wra 751*)
[GKM2012] WS1 *	Wray 16-137 *	CI* Westerlund 1 W 243 (W243)	HD 160529
GCIRS 34W	[MMC2010] LBV G0.120-0.048 *	qF 362 (FMM 362)	HD 168607
MWC 930 *	G24.73+0.69*	AFGL 2298*	P Cyg*

5 ACKNOWLEDGEMENTS

Spectral observations reported in this paper were obtained with the Southern African Large Telescope (SALT). AYK acknowledges support from the National Research Foundation (NRF) of South Africa. LNB acknowledges the Russian Science Foundation grant 14-22-00041.

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